UCDAVIS

PROJECT-LEVEL MITIGATION: WHAT AFFECTS DIESEL PARTICULATE MATTER EMISSIONS

By

Jeroen Van Houtte, PhD
Douglas Eisinger, PhD
Deb Niemeier, PhD, PE

Abstract

Background: Diesel Particulate Matter (DPM) is identified as a toxic air contaminant. In order to develop effective and cost-efficient mitigation measures, it is critical to understand vehicle-related engineering design parameters that are associated with DPM emissions at the transportation-project scale. This report aims at understanding the variables that affect mass emissions of $PM_{2.5}$ from diesel vehicles and identifying their implications for the development of project-specific mitigation measures.

Methods: This study reviewed driving modes and cycles used to measure diesel vehicle emissions and investigated operational parameters that affect DPM emissions. The effect of operational parameters on DPM emissions are typically measured based on standardized drive cycle dynamometer tests or live-traffic tests. We reviewed a range of studies associated with both methodological approaches, including gravimetric filter method (GFM) studies that measure total DPM emissions over a cycle, CO-binning studies that use a carbon monoxide time trace to infer conclusions about DPM emissions, time resolved studies that measure second-by-second DPM emissions, and roadside studies that validate theoretical emissions and dispersion models with ambient measurements.

Results: DPM emissions correlate well with cold start, load, acceleration and transient behavior, but large variations still exist in quantitative data measurements due to limited number of vehicles tested. The dominant operational parameters influencing DPM emission are transient operation and engine load. Various transportation project design approaches, such as reducing the number of starts and stops, smoothing traffic flow, and reducing road grade changes may reduce DPM emissions. Further research is needed to examine the impact of different parameters on DPM emissions based on larger test vehicle sets and changing vehicle fleet.

About The U.C. Davis-Caltrans Air Quality Project

http://AQP.engr.ucdavis.edu/

Department of Civil & Environmental Engineering
University of California
One Shields Ave., Davis, CA 95616
(530) 752-0586

Mission: The Air Quality Project (AQP) seeks to advance understanding of transportation related air quality problems, develop advanced modeling and analysis capability within the transportation and air quality planning community, and foster collaboration among agencies to improve mobility and achieve air quality goals.

History: Since the 1990s, the U.S. Federal Highway Administration and Caltrans have funded the AQP to provide transportation-related air quality support. Caltrans and AQP researchers identify and resolve issues that could slow clean air progress and transportation improvements.

Accessibility: AQP written materials and software tools are distributed through our website, peer-reviewed publications, conference presentations, training classes, formal reports and technical memoranda, and periodic newsletters.

Research: AQP investigations focus on project-level, regional-scale, and national-level assessments. Tools and publication topics cover pollutant-specific problems such as those involving particulate matter, carbon monoxide, carbon dioxide, ozone and air toxics; activity data collection and assessment for on- and off-road vehicles and equipment; mitigation options such as transportation control measures; policy analyses addressing transportation conformity and state implementation plan development; litigation support; and goods movement assessments.

Project Management

Principal Investigator and Director: Deb Niemeier, PhD, PE
Program Manager: Douglas Eisinger, PhD

Caltrans Project Manager: Mike Brady, Senior Environmental Planner
Air Quality and Conformity Coordination
Division of Transportation Planning, MS-32
California Department of Transportation
1120 N Street, Sacramento, CA 94274
(916) 653-0158

TABLE OF CONTENTS

1. INTRODUCTION

In order to implement effective and cost-efficient mitigation measures, it is critical to understand vehicle-related engineering design parameters that are associated with particulate matter (PM) emissions at the transportation-project scale. This discussion reviews what is currently known about the variables and mechanisms that affect the levels of diesel PM (DPM) emissions, which indicate elevated ambient concentrations in proximity to roads, and identifies implications for transportation facility design and operation.

The regulatory context for concern over DPM emissions focuses on two issues. First, in California, the California Air Resources Board (CARB) has identified DPM as a toxic air contaminant (TAC). The TAC designation triggered the creation and implementation by CARB of a diesel risk reduction program, resulting in ongoing efforts to modify the composition of diesel fuel and to implement more stringent emissions standards for on- and off-road diesel vehicles. The TAC definition highlighted the importance of reducing exposure to DPM. CARB has published land use guidance that recommends: "Avoid siting new sensitive land uses within 500 feet of a freeway, urban roads with 100,000 vehicles/day, or rural roads with 50,000 vehicles/day" (California Air Resources Board 2005).

Second, California and the federal government have established health-based air quality standards for exposure to PM. The National Ambient Air Quality Standards (NAAQS), for example, include thresholds for exposure to PM with an aerodynamic diameter smaller than either 10 (PM_{10}) or 2.5 ($PM_{2.5}$) microns. Studies indicate that almost all of the PM emitted by diesel vehicles is less than $PM_{2.5}$ in diameter (Kittelson 1998; Kleeman, Schauer et al. 2000). Therefore, DPM emissions may be a main contributor to elevated $PM_{2.5}$ concentrations at the project scale. The transportation conformity requirements mandate quantitative PM hot-spot analyses for new or expanded highway projects that involve a significant level of diesel vehicle traffic or will result in significant increase in the number of diesel vehicles.[1] Federal conformity approvals hinge on determinations that projects will not cause or contribute to violations of the

---

[1] An example project of concern that would trigger the conformity PM hotspot requirements is a project involving a facility with greater than 125,000 annual average daily traffic (AADT) and 8% or more of the AADT from diesel vehicles; see 40 CFR 93.123.

NAAQS. Mitigating DPM emissions at the project scale can, therefore, assist in reducing exposure to air toxics and achieving positive $PM_{2.5}$ conformity determinations.

Given existing regulatory requirements, this discussion focuses on understanding the variables that affect mass emissions of $PM_{2.5}$ from diesel vehicles. It should be noted, however, that there is an increasing emphasis on particle number and composition due to documented correlations with health effects (Pope III and Dockery 2006).

At the project level, a key goal is to discern how the gram per mile (g/mi) PM emission rate of diesel-powered vehicles will vary with different project-specific conditions. Much of the existing literature provides emission information based on engine or vehicle measurements that are indirect observations of real-world g/mi emissions. For example, some studies remove diesel engines from a truck, mount the engines onto a test bench, and measure emissions while the engine is separated from the vehicle. Such engine-test measurements offer insights into how engine parameters relate to emissions; however, the tests are an indirect simulation of actual driving conditions. The U.S. Environmental Protection Agency (EPA) certifies diesel engines using such an engine-test approach, based on the HDE-FTP cycle (see appendix) (Federal Register (FR) 2001).[2]

In an ideal world, project-specific mitigation insights could be drawn entirely from studies measuring actual vehicle emissions, as opposed to engine-test emissions. However, the engine-test literature is more extensive than the vehicle-test literature, reflecting the engine-test-based certification standards. Much of the engine-test literature provides detailed information based on measurements of relatively few or even single engines, without considering how the transmission and other vehicle components and characteristics affect the engine emissions. Some studies have bridged the gap between the engine-test literature and actual vehicle measurements by testing first the whole vehicle on a chassis dynamometer and subsequently the engine from that vehicle on a test bench (Yanowitz, Graboski et al. 2002). This discussion uses the vehicle-test literature

---

[2] Engine tests usually, and vehicle tests sometimes, report mass per unit of power (g/kWh or g/Bhp-hr). This power-specific measurement allows for comparison between engines, but for our purposes needs to be converted to g/mi.

and one study comparing vehicle-tests with engine-tests to draw insights into project-specific emissions.

2. A BRIEF PRIMER ON DRIVING MODES AND CYCLES USED TO MEASURE DIESEL EMISSIONS

Diesel-powered vehicles are operated under driving conditions that vary substantially depending upon their use. Refuse trucks, for example, are frequently driven short distances at slow speeds, with periodic stops and starts as they perform their work. In contrast, trucks servicing long-haul freight movement operate at freeway conditions for much of their driving, interspersed with periods of surface street activity and idling at freight transfer centers. A variety of test procedures have been developed to measure emissions from diesel engines and vehicles operating under various circumstances. These test procedures employ drive cycles that include a mix of starts, accelerations, cruise operations, decelerations, idle activity, and stops, depending upon the operating conditions being simulated. The findings discussed in this report draw upon test results from a range of drive cycles. The appendices to this document provide graphic and text descriptions of each of the cycles cited in the literature discussed here. When a vehicle is subjected to a drive-cycle on a dynamometer, the emissions are gathered in either a "bag" or on a second-by-second basis. During bag measurements, pollutant mass is collected during a portion or all of a test cycle; a single bag can thus represent the total mass of pollutants emitted over various driving conditions and several minutes. Second-by-second measurements allow emissions data to be matched to individual driving conditions such as cruise, acceleration, or deceleration activities. Both bag and second-by-second data are useful, but the second-by-second data is best at helping us understand how emissions vary with the operational parameters that would be affected at the project level. There are, however, only a limited number of studies that have measured second-by-second diesel PM emissions. Therefore, this discussion reviews and draws insights from studies that collected both bag and second-by-second data.

3. PARAMETERS THAT AFFECT DPM EMISSIONS

DPM is mostly a product of "rich," or insufficiently lean, combustion, which can occur at high loads or during transient operations (Taylor, Clark et al. 2004). The literature shows that DPM emissions tend to be affected by three categories of parameters: vehicle characteristics, fuel composition, and operational parameters. Vehicle characteristics include, for example, engine type, engine size, exhaust-treatment technology, and vehicle weight. Generally, emissions are reported to rise with older technology, larger engines and heavier vehicles (Yanowitz, Graboski et al. 1999; Clark, Kern et al. 2002).[3] Fuel composition refers to the chemical constituents of the diesel fuel itself. Regulatory efforts have been made over the years to mandate fuel formulations that enhance combustion and reduce degradation of emission control systems. An example of a regulated fuel composition element is sulfur content. Sulfur-related emissions, such as SO_2, rise as sulfur content increases; in addition, sulfur impedes the efficacy of catalytic converters. For operational parameters, DPM emissions typically rise with more aggressive driving styles, with rising power demand, with more "transient" operation (stop-and-go and variable acceleration and deceleration activity), with cold starts, and with longer idling.

For project mitigation, the factors that can be addressed (at the project level) are the operational parameters. Fuel composition and vehicle characteristics are mostly beyond the control of a local or corridor-level project. Speed, acceleration, and engine load can be influenced with the design of roads and signals, and through actions such as the enforcement of speed and weight limits. Cold starts and idling can be reduced or moved in space or time with parking and idling restrictions.

The research that discusses the effect of operational parameters on DPM emissions can be divided into two main methodological approaches: standardized drive cycle dynamometer tests and live-traffic tests. The former has the advantage of being repeatable and more easily comparable to other studies, the latter is arguably more suited to estimating real-world, facility-

---

[3] Not only do vehicle emissions rise with older engine technology, but the engine technology also interacts with the way in which operational parameters affect emissions. Turbocharged engines, for example, are generally more sensitive to transient operation than non-turbocharged ones Taylor, S., N. N. Clark, et al. (2004). "Diesel emissions prediction from dissimilar cycle scaling." Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering **218**(3): 341-352.

specific emissions. The bulk of the literature is based on the dynamometer approach: gravimetric filter method (GFM) studies measuring total DPM emissions over a cycle, CO-binning studies that use a carbon monoxide time trace to infer conclusions about DPM emissions, and studies measuring second-by-second time-resolved DPM emissions. Under the live-traffic approach, we find roadside studies that validate theoretical emission and dispersion models with ambient measurements, as well as mobile laboratory measurements based on instrumented diesel vehicles.

GFM Studies

Most studies measure PM using the gravimetric filter method (GFM), which is also used for the federal reference method; it is analogous to a bag-type test and is limited to measuring the total emissions of a test cycle, without collecting second-by-second data. Differences in emissions between different tests are then explained based on the different test cycle characteristics.

In the Colorado Northern Front Range Air Quality Study, 21 HDDV from a variety of applications (bus, utility, delivery) were measured using three different cycles (CBD, HDT and WVU-5-peak; see appendix). The vehicle weights ranged from 11,050 lb to 80,000 lb gross (GVWR), from 1981 to 1995 in model year, and from 5,320 to 595,606 miles on the odometer. Cold start was found to increase DPM emissions on average by 11% compared to warm start (Graboski, McCormick et al. 1998; Yanowitz, Graboski et al. 1999). By expressing emissions as fuel-specific rather than distance-specific the difference between the three drive cycles was somewhat reduced, indicating some correlation between fuel use and PM emissions. While fuel use is not an operational parameter in the sense that the operator does not directly control it, fuel use is known to be correlated with operational parameters, most notably engine load.

In a comparison study of three diesel buses and three CNG buses (18,780 lb GVWR, model year 1997) on the CBD and WVU-5-peak cycles and on the WVU-5-mile route (a more aggressive version of the 5-peak cycle), differences in the rates of acceleration were found to affect emissions. When drivers aggressively followed the CBD test cycle, acceleration PM emissions more than doubled from 3g/mi (+/-1g/mi) to 7g/mi (+/- 0.5 g/mi), compared to the non-aggressive mode of following the test cycle. In the aggressive mode, the driver tried to follow a

speed trace exactly and typically slightly over-accelerated the vehicle at the onset of acceleration, and then eased up on the pedal to match the trace. In the non-aggressive or conservative mode, the driver was given more tolerance while following trace; the driver attempted to follow a constant rate throughout accelerations, making adjustments in pedal position slowly and smoothly (Clark, Gautam et al. 1999). Aggressive acceleration modes resulted in up to a tenfold increase in CO concentration peaks as measured during the test. These findings are of relevance for project-specific considerations because PM and CO emissions are correlated (Clark, Gautam et al. 1999) and aggressive acceleration events occur more frequently during congested travel conditions.

The same research group also reported test results for a Kenworth truck-tractor with high power to weight ratio and a Flint bus (38,000 lb GVWR) showing, respectively, 50% and 100% higher PM emissions for the WVU-5-mile route than for the less aggressive WVU-5-peak cycle (Nine and Clark 2000; Clark, Kern et al. 2002). In another study by the same group on a GMC box truck and a Peterbilt truck tractor (Nine and Clark 2000), however, the WVU-5-mile route emissions did not consistently exceed those of the less aggressive WVU-5-peak cycle. This may be explained by these two vehicles' inability to appreciably exceed the power demands of the 5-peak cycle.

A subsequent study using two buses with electronically controlled[4] engines and a snowplow with a mechanical engine found good correlation between cycle PM mass emissions and cycle severity, defined as a function of the change in acceleration horsepower over the length of the test (Yanowitz, Graboski et al. 2002). As such, a cycle is more severe if it includes more and harder accelerations, while the length of the acceleration and the top speed do not influence severity. All vehicles were run on the HDT cycle; the snowplow was run with 47%, 70%, and 97% of GVWR load, the buses only at 90% load. The buses were also run on the CBD cycle at 90% load. The correlation between cycle severity and PM mass emissions was especially strong for more modern, electronically controlled engines.

---

[4] Electronically controlled engines have more precise control over fuel injection as it is controlled by software and solenoid valves, rather than the timing and throttle valves in mechanical engines.

Shah, Cocker et al. (Shah, Cocker III et al. 2004) from CE-CERT at U.C. Riverside found that high speed cruising causes fewer PM mass emissions per mile than transient and creep (very slow) driving modes of the Heavy Heavy-Duty Diesel Truck HHDDT cycle. Each mode began and ended from a parked position. The cruise mode mainly consisted of a half-hour of driving between 50 and 60 mph; the transient mode had stops approximately every two minutes and peak speeds in the 25-45 mph range; the creep mode represented stop-and-go traffic with peak speeds between 3 and 8 mph.

The CE-CERT mobile laboratory measured PM emissions for 11 vehicles model year 1996-2000. Fleet average elemental and organic carbon emissions were highest for creep mode (0.95 g/mi), followed by transient driving (0.62 g/mi), and cruise (0.25 g/mi). While Shah, Cocker et al. reported large standard deviations on these numbers due to variations between makes and models, the overall insight gained from their work is that DPM emissions are reduced when traffic moves smoothly at cruising speed.

The CE-CERT findings of high creep and transient mode emissions were confirmed in a separate investigation, called the E55/E59 study, funded through the Coordinating Research Council (CRC). In a study of 25 HHDDTs, Gautam, Clark et al. (Clark, Gautam et al. 2003) found that distance-specific creep emissions may be approximately twice as high as transient emissions, and four times as high as cruise emissions (Gunst 2003). This difference, where per-mile creep emissions far exceed transient and cruise emissions, was even starker in subsequent work with 10 HHDDTs and 9 Medium Heavy-Duty Trucks (MHDT) where the average creep, transient and cruise PM emissions were, respectively, 7.92 g/mi, 2.21 g/mi, and 0.41 g/mi (Clark, Gautam et al. 2005). The implication of this research is that, to minimize DPM emissions, projects should eliminate obstacles that worsen traffic flow or require trucks to stop (Figure 1).
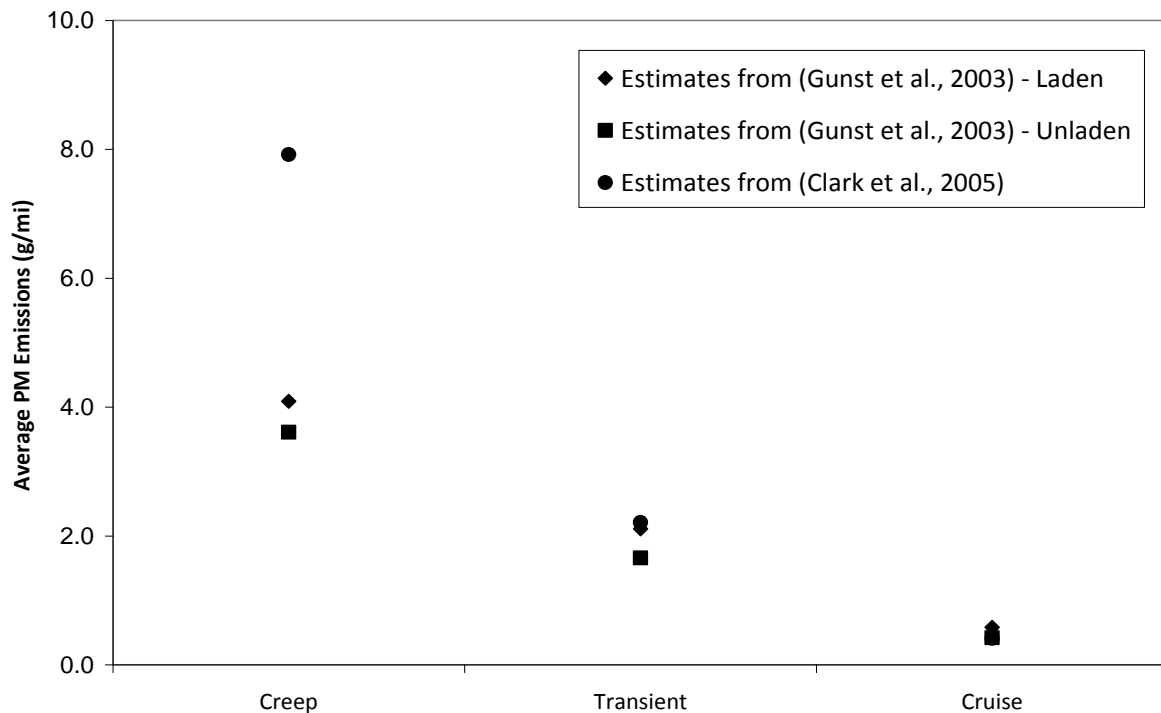
Figure 1. Average PM emissions based on CRC E-55 measurements of cycle effects; adapted from (Gunst, 2003) and (Clark et al., 2005).

Some research has characterized the modal composition of a drive cycle using properties of each cycle (average speed, stops per mile, percentage idle and kinetic energy). A modal analysis of 11 vehicles predicted cycle emissions based on individual cycle's similarity to idle, creep, transient, and cruise operations that occur with the Heavy Heavy-Duty Diesel Truck (HHDDT) cycles. The investigators found that predictions for UDDS cycle emissions correlated with emissions measurements with an r^2 of 0.85 (Taylor, Clark et al. 2004). The implication is that, across various test cycles, the amount of creep, transient or cruise driving modes explains much of the variance in emissions.

In another study looking at the relationship between operational parameters and HDDV emissions, Kear and Niemeier (Kear and Niemeier 2006) developed a model to predict DPM emissions variability as a function of engine activity. The model development process employed emissions data obtained from the CRC E55/E59 study mentioned earlier, and covered results from 531 tests of 34 heavy-duty vehicles on six cycles (the AC5080, UDDS, and four cycles based on the HHDDT creep, cruise and transient modes; see appendix for a description of the

cycles). This model used inverted speed (hours per mile) and intensity per mile as predictor variables, where intensity was defined as the integral of positive horsepower with positive acceleration.

The resulting "Intensity Model" coupled real-world second-by-second speed and power data with PM emissions data from HDDV chassis dynamometer tests. The researchers found that, as HDDV average speeds increase beyond approximately 20 mph, DPM g/mi emissions decline. The same study also found that as HDDV link-level speeds fell below 10 mph, emissions declined with declining speed. The researchers noted that the low-speed (<10 mph) findings contradicted traditional emissions model results based on California's EMFAC model. One explanation offered for the disparity was that real-world data showed that links with an average speed below 10 mph have relatively smooth speed traces and less variable driving behavior, resulting in lower emissions. In contrast, traditional EMFAC modeling for trips with an average speed below about 10 mph are based on data sets where most of the VMT for the trip occurred at speeds above 10 mph. These trip-based data include greater driving behavior variability and thus higher emissions (UC Davis-Caltrans Air Quality Project 2005).

Kear and Niemeier reported an r^2 of 0.65 for their model compared to an r^2 of 0.37 and 0.15 for alternative models based on severity (as defined above) and modal analysis, respectively (Kear and Niemeier 2006). The implications from this work are that highly transient driving modes are correlated with high PM mass emissions, and that higher speeds generally reduce g/mi emission rates. The findings are important from a project-level perspective since they imply that facility improvements that increase travel speeds beyond 20 mph will tend to reduce per-vehicle emissions. Here, however, we also see low emissions with low speed, under the assumption that the variability in the speed is low also, which is not the case in the HHDDT creep mode as reported by Shah, Cocker et al. (Shah, Cocker III et al. 2004) and Gautam, Clark et al (Clark, Gautam et al. 2005).

CO Binning Studies

Another approach to studying the effects of modal operations on emissions is to measure CO emissions and then infer DPM emission implications. In part, these studies are relying on the

positive correlation exhibited between PM measured using GFM and total CO emissions measured over a test cycle. This has allowed researchers to use second-by-second CO emissions data to allocate PM emissions to time segments (g/s) and then to bin the results by acceleration and speed. On a study of three buses, the correlation between PM and CO was better (r^2=0.956, slope=0.145) (Clark, Gautam et al. 1999) than on a study of 21 diverse vehicles (r^2=0.76, slope=9.8) (Yanowitz, Graboski et al. 1999). The conclusions regarding PM emissions of both these studies were based solely on total GFM emissions over the test cycles (as discussed above).

Data from six buses tested on three cycles[5] were provided in (Clark, Gautam et al. 2003) and for a truck in (Cambridge Systematics, Battelle et al. 2002); the studies indicated an order of magnitude less emissions during deceleration than during heavy acceleration. Unexplained anomalies like the absence of data for cruise around 5 mph and 15 mph in the former study and a sudden drop in cruise emissions at 50 mph in the latter study, keep us from drawing further conclusions from these studies. It is also important to note that the findings are not based on direct PM measurements, that the alignment of real-time measurements with the actual engine mode may introduce bias, and that some data quality issues exist.

Time Resolved Studies

Second-by-second time-resolved PM emissions measurements represent another way to examine the relationship between modal operations and emissions. Researchers have used second-by-second studies to better understand emissions qualitatively and to correlate emissions with speed and acceleration (Holmen and Qu 2004; Shah, Johnson et al. 2006). Studies have employed various PM measurement techniques; thus, it is difficult to determine whether, across different studies, variability in the findings is partly due to the measurement technique used. Example measurement approaches include indirect measurements that relate light extinction to PM, and direct PM observations using tapered element oscillating microbalances (TEOMs) and laser induced incandescence.

Hofeldt and Chen (Hofeldt and Chen 1996) found that 80% of PM mass is emitted during acceleration, even in a cycle where this acceleration only accounts for 45% of fuel consumption.

---

[5] CBD, Kern, and City Suburban Heavy Vehicle Route (CSHVR)

They reached this conclusion based on light extinction measurements on five 1994 buses on idle, CBD, UDDS, 55 mph steady state (SS55), and New York Bus (NYB) cycles (Hofeldt and Chen 1996).

As a part of the cycle severity work reported above, Yanowitz et al. used a TEOM engine test procedure to find that an instantaneous increase in HP is related to increased PM emissions. These engine test bench results in g/s (smoothed over ten-second averages) were consistent with their cycle severity measures (Yanowitz, Graboski et al. 2002). The implications from this work are that transient operations (meaning more stop-and-go or more slow-down-then-accelerate-type driving) worsen PM emissions, both on a g/sec and a g/mi basis.

Roadside Studies

Another way to research effects of operational parameters on emissions is to postulate a theoretical model and validate it with measurements of roadside ambient air concentrations, traffic data, and a dispersion model. Two studies (Singh and Huber 2000; Singh, Huber et al. 2003) postulated a nonlinear relationship between DPM and average speed based on power and fuel consumption estimates and validated it with ambient measurements.[6] Researchers developed an emissions model for U.S. vehicles, based on European speed data. The model showed constant emissions with speed until 12 mph (19 km/h) followed by a two-segment linear decrease reaching approximately half of the low-speed emissions at 50 mph (80 km/h) and remaining constant for higher speeds (Figure 2). These roadside studies showed higher emissions at low average speed (typical of creep) compared to lower emissions typical of cruise. An earlier model developed for European vehicles (Singh and Colls 2000) predicted higher emissions at freeway speeds; however, the U.S. model, developed later, overturned the European-based findings, at least for the U.S. vehicles and model years observed. Also, cold start emissions were reported to be between 25% and 100% higher than warm start (Singh and Huber 2000).

---

[6] The speed/emissions relationship was tested in an urban canyon with a dispersion model for such environment and found to explain variability in the ambient concentrations (r^2=0.6).
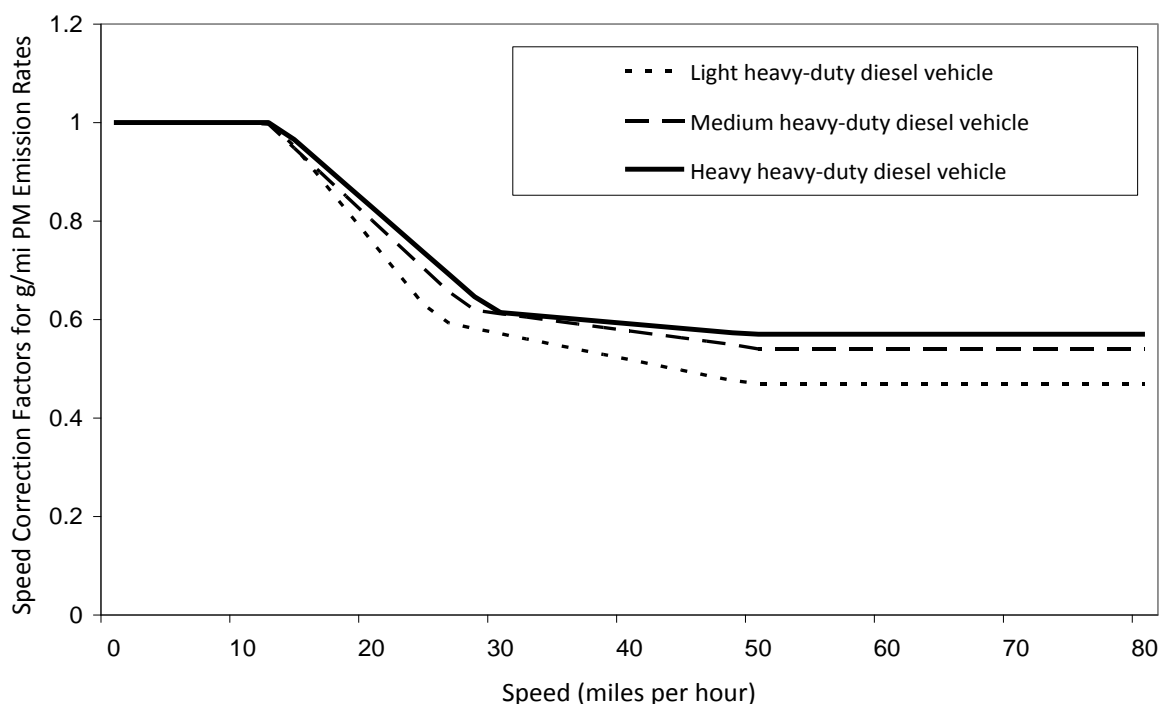
Figure 2. Speed correction factors for heavy-duty diesel vehicles developed for a U.S. vehicle-based model; adapted from (Singh et al., 2003)

Real-time live-traffic data (not on dynamometers) from U.C. Riverside's mobile laboratory showed lower PM emissions for cruising operation than for arterial or congested operation, and higher PM emissions for high-power, wide-open throttle accelerations (WOT, or "flooring" the accelerator) (Nigam, Chaudhary et al. 2006). Arterial operations have increased start-and-stop activity compared to cruise conditions more typical of uncongested freeway operations; arterials can thus be considered comparable to the transient driving modes evaluated in these and the other studies discussed.

4. CONCLUSIONS AND RESEARCH NEEDS

PM emissions correlate well with cold start, load, acceleration and transient behavior, but quantitative data are still elusive, due to difficulties in measurement as well as large variations between vehicles and relative low numbers of vehicles tested. While most studies are limited due to the low number of vehicles studied, and the large variance between vehicles found in the

larger studies, it is striking that the studies agree on the correlations between operational parameters and PM emissions (Table 1, Table 2). An uncertain parameter is average speed (only three studies examined this parameter; see Tables 1 and 2), showing both a negative correlation and a nonlinear u-shaped correlation. This can be explained by the different operational modes that may correspond to a single average speed: driving steadily at 10 mph will give the same average speed as driving with a peak speed of 25 mph and frequent stops. Neither peak speed nor instant speed are reported on in the literature, except in studies of particle number (Holmen and Qu 2004), or in combination with horsepower to calculate intensity. Among the limited data available, a consensus appears to exist that low average speed causes high emissions in highly transient modes like the HHDDT creep mode, and lower emissions in more steady state modes.

The dominant operational parameters influencing diesel PM emissions are shown to be transient operation and engine load. Measures that could be taken, or design triggers that can be considered to improve these parameters are, for example: improving traffic flow, reducing the number of stops or sharp turns and subsequent accelerations, reducing and smoothing road grade changes, and changing vehicle routing to reduce the number and/or slope of steep uphill grades, enforcing speed limits, imposing weight restrictions, and limiting multiple trailers (which would reduce weight and, therefore, engine load) (Table 3).

Except for average speed, the other operational parameters, as listed in Tables 1 and 2, show a positive correlation with emissions where measurable: as the parameters increase, so do the emissions. Various design approaches, such as reducing the number of starts and stops, or smoothing traffic flow, can reduce these parameters and therefore also the emissions. Table 3 identifies these approaches, called "design triggers," and relates how their implementation can trigger reductions in power, speed, and time-based parameters, and, therefore, trigger reduced emissions. Some parameters, however, are difficult to influence via project design. For example, the aggressiveness of acceleration depends much more on the characteristics of the driver, than on any design trigger. Also, secondary effects may need to be considered: while limiting the size and speed of trucks may reduce engine load and emissions from each vehicle, it may also increase the total number of vehicles traveling the corridor, possibly worsening congestion and increasing emissions. Finally, parking restrictions can be applied in many different ways, and it

is not possible for us to give generally applicable effects of such restrictions. This design trigger, even more than the others, can increase, as well as decrease emissions, depending on the implementation and local circumstances.

As illustrated by the findings in Tables 1-3, research indicates that a number of project-specific parameters can be adjusted to reduce DPM emissions. However, the findings are based on limited data derived from studies that have tested very few vehicles. For example, findings related to average speed are based largely on one GFM study that measured emissions from 11 vehicles. Further research is needed to confirm and build upon the findings to date. To draw conclusions with statistical significance, a larger number of vehicles must be tested especially with second-by-second data. Furthermore, each study discussed in this paper tested a narrow set of parameters; an overarching study that compares the different parameters on the same vehicles would allow for better comparisons across the studies to determine which parameters are most important. Finally, the characteristics of the U.S. vehicle fleet are expected to change given the engine technology and fuel composition changes implemented in the U.S. during 2006 and 2007. An important research need is to monitor real-world emissions from the vehicle fleet certified to meet model year 2007 and later emission requirements.

Table 1. Summary of GFM studies and operational parameters (+ indicates a positive correlation with PM mass emissions, O indicates little or no correlation, - negative correlation, U nonlinear correlation; if the box is empty, findings associated with that parameter were not published as part of the study cited).

Authors	Kear and Niemeier	Gautam, Clark, et al.	Graboski, McCormick, et al.	Clark, Gautam, et al.	Shah, Cocker, et al.	Taylor, Clark, et al.	Yanowitz, Graboski, et al.	Clark, et al.	Nine, Clark, et al.	Clark, Kern, et al.
Year	2006	2003	1998	2005	2004	2004	2002	1999	2000	2002
Number of vehicles	34[a]	25	21	19	11	11[b]	3	3	2	2
Type of measurement	GFM	GFM	GFM	GFM	GFM	GFM	GFM	GFM	GFM	GFM
Test cycles	6 cycles	HHDDT	CBD, HDT, WVU 5-peak	HHDDT	HHDDT	HHDDT	CBD, HDT	CBD, WVU 5-peak, WVU 5-mile	WVU 5-peak, WVU 5-mile [c]	WVU 5-peak, WVU 5-mile
Power-based parameters										
Aggressive acceleration								+	O	+
Cycle severity (HP increase)							+			
Fuel use			+							
Intensity	+									
Speed-based parameters										
Average speed						-				
Creep > Transient > Cruise		+		+	+					
Kinetic energy						+				
Stops per mile						+				
Time-based parameters										
Cold start			+							
Pct. idle						+				

Note: + indicates a positive correlation with PM mass emissions, O indicates little or no correlation, - indicates negative correlation; empty boxes reflect that findings associated with the parameter were not published as part of the study cited.

[a] These 34 vehicles are a subset of the combined 44 in (Clark et al., 2003) and(Clark et al., 2005).

[b] These 11 vehicles are a subset of the 25 in (Clark et al., 2003).

[c] The paper reported on 18 drive cycles, but only the two WVU cycles are used to evaluate operational parameters (Nine et al., 2000).

Table 2. Summary of non-GFM studies and operational parameters (+ indicates a positive correlation with PM mass emissions, O indicates little or no correlation, - negative correlation, U nonlinear correlation, if the box is empty, findings associated with that parameter were not published as part of the study cited).

Authors	Clark, Gajendran, et al.	Hofeldt and Chen	Cambridge Systematics, Batelle, et al.	Nigam, Chaudhary, et al.	Yanowitz, Graboski, et al.	Singh and Huber	Singh, Huber et al.
Year	2003	1996	2002	2006	2002	2000	2003
Number of vehicles	6	5	3	1	1 engine	n.a.	n.a.
Type of measurement	CO bin	Light extinction	CO bin	Trailer	TEOM	Roadside	Roadside
Test cycles	CBD, CSHVR, Kern	CBD	Inventory Highway Cycle (IHC), CSHVR	n.a.	HDE-FTP	n.a.	n.a.
Power-based parameters							
Acceleration	+	+	+				
Engine Load						+	+
Fuel Use						+	+
HP increase					+		
Speed-based parameters							
Creep > Transient > Cruise				+ [a]			
Average speed						U	-
Congestion				+			
Time-based parameters							
Cold Start						+	+

Note: + indicates a positive correlation with PM mass emissions, O indicates little or no correlation, - indicates negative correlation, U indicates nonlinear correlation; empty boxes reflect that findings associated with the parameter were not published as part of the study cited.
[a] Arterial emissions were shown higher than cruise emissions; arterial corresponded largely with transient; creep-related findings were not published (Nigam et al., 2006).

Table 3.   Practical transportation project design triggers and their relation to per-vehicle operational parameters (- indicates a negative correlation between the parameter and the trigger, + a positive correlation, an empty box indicates no known correlation).

Design Triggers	Power-based parameters							Speed-based parameters					Time-based parameters	
	Acceleration	Aggressive acceleration	Cycle severity (HP increase)	Engine load	Fuel use	HP increase	Intensity	Average speed	Congestion	Creep > Transient > Cruise	Kinetic energy	Stops per mile	Cold start	Percent idle
Improving traffic flow	-	a	a	-	-	-	-	+ b	-	-		-	c	-
Reducing number of stops, sharp turns	-	a	a	-	-	-	-	+ b	-	-		-	c	-
Reducing number and slope of uphill grades	-			-	-	-	-	+ b	-	-	-		c	
Enforcing speed limits				-				- b	c		-		c	
Imposing weight restrictions				-	-	-	-		c		-		c	
Limiting multiple trailers				-	-	-	-		c		-		c	
Parking Restrictions					d				d				+/-	+/-

Note: - indicates a negative correlation between the parameter and the trigger, + indicates a positive correlation, an empty box indicates no known correlation.
[a] While practical measures may reduce the number of accelerations, they usually cannot influence the severity or hardness of each acceleration.
[b] Average speed is the one parameter in this table for which the correlation with emissions is not considered positive.
[c] If trucks are larger or get to the destination faster, fewer trucks may be needed, especially in short-haul or drayage operation. In this case the number of cold starts would be reduced; in some cases, congestion may also be reduced.
[d] Consider the induced traffic, analogous to light-duty vehicles looking for a parking spot.

5. APPENDIX – DRIVE CYCLES

Most studies referenced in this paper report on dynamometer measurements of PM mass emissions. Dynamometer measurement results vary greatly with the drive cycle to which the vehicle or engine is subjected. This appendix provides summary information concerning the most common drive cycles used in the referenced studies.

5.1 Heavy-Duty Engine FTP Transient Engine Cycle (HDE-FTP)

The HDE-FTP cycle is the basis on which engines are certified in the U.S. It is designed to represent truck and bus operation in cities as well as between cities (Code of Federal Regulations (CFR) Title 40). The four phases of the cycle include a) NYNF (New York Non Freeway) phase representing frequent stops and starts under light urban traffic condition; b) LANF (Los Angeles Non Freeway) phase reflecting few stops under congested urban traffic condition; c) LAFY (Los Angeles Freeway) phase simulating congested expressway traffic condition; and d) the repeated NYNF phase (DieselNet, 2008). The entire cycle therefore comprises a wide range of different speeds and loads through a sequence of cold start, idling, acceleration, and deceleration phases.

5.2 EPA Heavy Duty Transient Truck Cycle (HDT)

The HDT test cycle is also known as the Heavy Duty Urban Dynamometer Driving Schedule (HD-UDDS) or Test-D. It is designed to be used as a basis for the HDE-FTP engine cycle for chassis dynamometer testing of trucks and buses operating in cities as well as between cities. The cycle has duration of 1060 seconds, average speed of 18.8 miles per hour (mph), and maximum speed of 58 mph (U.S. Environmental Protection Agency, 2008).

5.3 Central Business District Cycle (CBD)

The CBD Cycle is designed to simulate activities observed during urban bus operations (Society of Automotive Engineers International, 1997). The cycle's duration is 560 seconds, with 14 similar small cycles of acceleration, cruise, deceleration, and idle, and average speed of 12.6 mph and maximum speed of 20 mph, respectively (DieselNet, 2008).

5.4 West Virginia University Truck 5-peak Cycle (WVU 5-peak)

The WVU 5-Peak Cycle was designed for general truck chassis testing and it limits the maximum power applied during acceleration events to obtain a single second-by-second speed trace that can be achieved by most heavy-duty vehicles (Clark and McKain, 1995; Clark et al., 1994). The cycle consists of five phases with peak speeds changing from 20 to 40 mph with 5 mph increment.

5.5 West Virginia University Truck 5-Mile Route (WVU 5-mile)

The WVU 5-Mile Route is a modification of the WVU 5-Peak cycle, requiring the operator to accelerate with maximum power instead of following the WVU 5-Peak acceleration rate that was designed so that all vehicles could meet it (Clark et al., 1994). To keep the total distance of both tests identical the lengths of the cruise sections are adjusted as needed. The total time for this route is therefore dependent on the power of the vehicle tested.

5.6 Heavy-Heavy-Duty Diesel Truck Cycle (HHDDT)

The HHDDT Cycle is a set of vehicle cycles designed to differentiate between different modes of truck operation (California Air Resources Board, 2005). The HHDDT cycle series consist of a 253-second idle and creep mode, a 668-second transient mode, and a 2083-second high-speed cruise mode.

5.7 Other Cycles

In addition to the cycles cited above, there are a variety of other specialized cycles developed and used by various researchers. Some of these additional cycles were employed in the studies cited in this paper, such as the City-Suburban Heavy Vehicle Route (CSHVR or CSR) for delivery trucks, the Kern cycle developed to collect instantaneous data at several steady-state operating points (Nine et al., 2000), and the AC5080 (or AC50/80) cycle developed as a short alternative to the UDDS for roadside testing (National Environment Protection Council, 2000).

6. REFERENCES

California Air Resources Board (2005). Air quality and land use handbook: a community health perspective.

Cambridge Systematics, Battelle, et al. (2002). Heavy-duty vehicle emissions, final report for NCHRP project 25-14.

Clark, N. N., M. Gautam, et al. (1999). "Diesel and CNG transit bus emissions characterization by two chassis dynamometer laboratories: results and issues." SAE Technical Paper Series **1999-01-1469**.

Clark, N. N., M. Gautam, et al. (2003). Heavy-Duty Vehicle Chassis Dynamometer Testing for Emissions Inventory, Air Quality Modeling, Source Apportionment and Air Toxics Emissions Inventory: Project E-55/59 Phase 1 Final Report.

Clark, N. N., M. Gautam, et al. (2005). Heavy-Duty Vehicle Chassis Dynamometer Testing for Emissions Inventory, Air Quality Modeling, Source Apportionment and Air Toxics Emissions Inventory: Project E-55/59 Phase 2 Final Report.

Clark, N. N., J. M. Kern, et al. (2002). "Factors Affecting Heavy-Duty Diesel Vehicle Emissions." Journal of the Air & Waste Management Association **52**: 84-94.

Clark, N. N. and D. L. McKain (1995). "Transient Chassis Cycles for Heavy Duty Trucks and Tractors." International Journal of Heavy Vehicle Systems **2**(2): 143-159.

Clark, N. N., D. L. McKain, et al. (1994). "Chassis test cycles for assessing emissions from heavy-duty trucks." SAE Technical Paper Series **941946**.

Code of Federal Regulations (CFR) Title 40 **Part 86.1333**.

Federal Register (FR) (2001). **66**: 5186.

Graboski, M. S., R. L. McCormick, et al. (1998). Heavy-Duty Diesel Vehicle Testing for the Northern Front Range Air Quality Study. Golden, Colorado, Colorado Institute for Fuels and High Altitude Engine Research.

Gunst, R. F. (2003). Statistical analysis of CRC E-55/E-59 phase 1 data: final report CRC project no. E-71.

Hofeldt, D. L. and G. Chen (1996). "Transient particulate emissions from diesel buses during the central business district cycle." SAE Technical Paper Series **960251**.

Holmen, B. A. and Y. G. Qu (2004). "Uncertainty in particle number modal analysis during transient operation of compressed natural gas, diesel, and trap-equipped diesel transit buses." Environmental Science & Technology **38**(8): 2413-2423.

Kear, T. and D. A. Niemeier (2006). "On-road heavy-duty diesel particulate matter emissions modeled using chassis dynamometer data." Environmental Science & Technology **40**(24): 7828-7833.

Kittelson, D. B. (1998). "Engines and nanoparticles: a review." Journal of Aerosol Science **29**(5/6): 575-588.

Kleeman, M. J., J. J. Schauer, et al. (2000). "Size and Composition Distribution of Fine Particulate Matter Emitted from Motor Vehicles." Environmental Science and Technology **34**(7): 1132-1142.

National Environment Protection Council (NEPC) (2000). In-Service Emissions Performance - Phase 2: Vehicle Testing - Appendices.

Nigam, A., A. K. Chaudhary, et al. (2006). Continuing Investigations Into Real-World and Real-Time Emissions from Heavy-Duty Diesel Vehicles: Results from an Expanded Test Matrix, Coordinating Research Council.

Nine, R. D. and N. N. Clark (2000). "Effect on emissions of multiple driving test schedules performed on two heavy-duty vehicles." SAE Technical Paper Series **2000-01-2818**.

Pope III, C. A. and D. W. Dockery (2006). "Health effects of fine particulate air pollution: lines that connect." Journal of the Air & Waste Management Association **56**: 709-742.

Shah, S. D., D. R. Cocker III, et al. (2004). "Emission Rates of Particulate Matter and Elemental and Organic Carbon from In-Use Diesel Engines." Environmental Science & Technology **38**(9): 2544-2550.

Shah, S. D., K. C. Johnson, et al. (2006). "Emission rates of regulated pollutants from on-road heavy-duty diesel vehicles " Atmospheric Environment **40**(1): 147-153.

Singh, R. B. and J. J. Colls (2000). "Development and preliminary evaluation of a particulate matter emission factor model for European motor vehicles." Journal of The Air & Waste Management Association **50**(10): 1805-1817.

Singh, R. B. and A. H. Huber (2000). "Development of a microscale emission factor model for CO for predicting real-time motor vehicle emissions." Journal of the Air & Waste Management Association **50**(11): 1980-1991.

Singh, R. B., A. H. Huber, et al. (2003). "Development of a microscale emission factor model for particulate matter for predicting real-time motor vehicle emissions." Journal of the Air & Waste Management Association **53**(10): 1204-1217.

Society of Automotive Engineers International (SAE) (1997). Standard J1376: Fuel Economy Measurement Test (Engineering Type) for Trucks and Buses.

Taylor, S., N. N. Clark, et al. (2004). "Diesel emissions prediction from dissimilar cycle scaling." Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering **218**(3): 341-352.

U.S. Environmental Protection Agency. (2008). "Testing and Measuring Emissions: Dynamometer Driver's Aid." from http://www.epa.gov/nvfel/testing/dynamometer.htm.

UC Davis-Caltrans Air Quality Project (2005). Speed and Emissions: New Insight on Diesel Trucks and Particulate Matter.

Yanowitz, J., M. S. Graboski, et al. (2002). "Prediction of In-Use Emissions of Heavy-Duty Diesel Vehicles from Engine Testing." Environmental Science & Technology **36**(2): 270-275.

Yanowitz, J., M. S. Graboski, et al. (1999). "Chassis Dynamometer Study of Emissions from 21 In-Use Heavy-Duty Diesel Vehicles." Environmental Science & Technology **33**(2): 209-216.